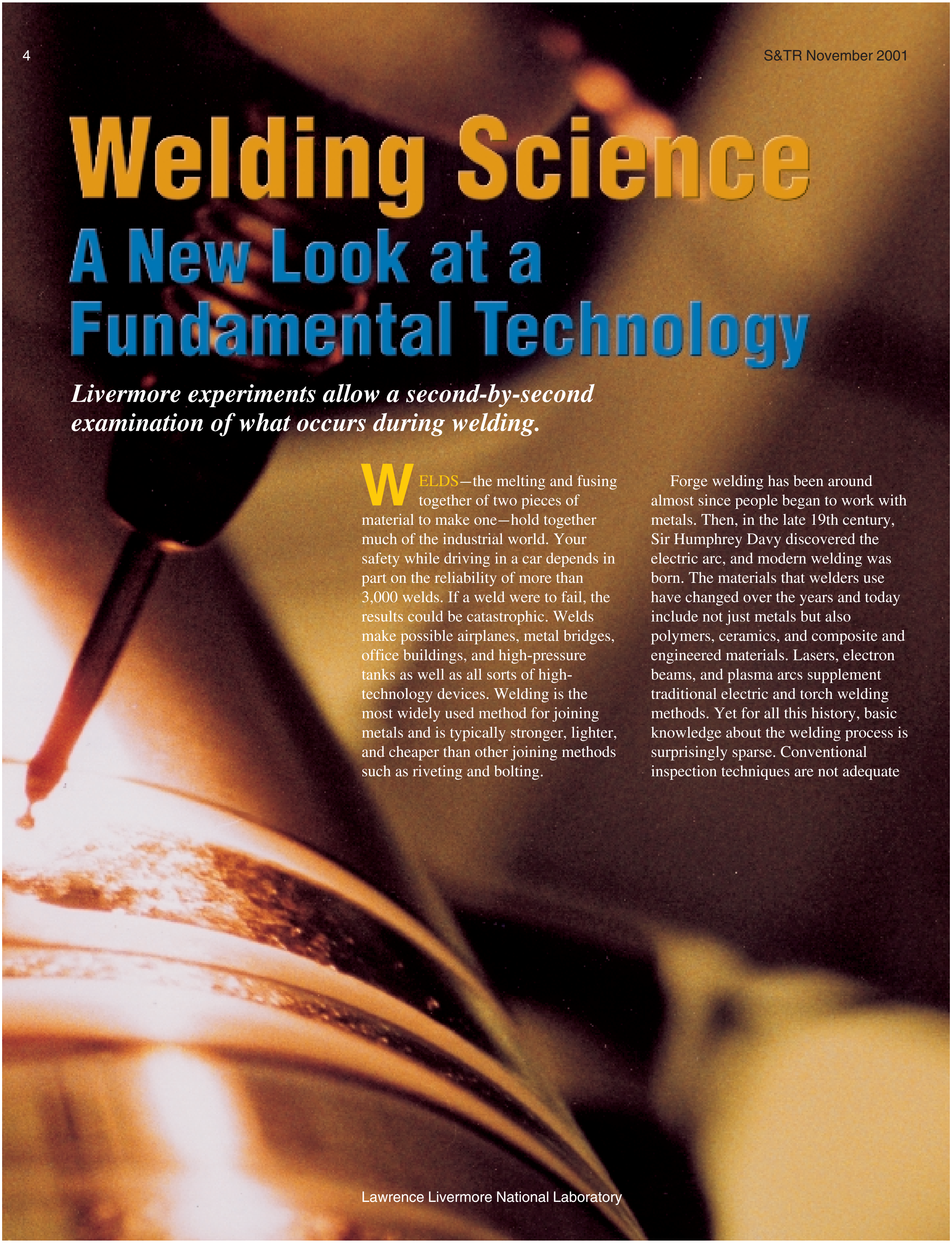


# Welding Science

## A New Look at a Fundamental Technology

***Livermore experiments allow a second-by-second examination of what occurs during welding.***

WELDS—the melting and fusing together of two pieces of material to make one—hold together much of the industrial world. Your safety while driving in a car depends in part on the reliability of more than 3,000 welds. If a weld were to fail, the results could be catastrophic. Welds make possible airplanes, metal bridges, office buildings, and high-pressure tanks as well as all sorts of high-technology devices. Welding is the most widely used method for joining metals and is typically stronger, lighter, and cheaper than other joining methods such as riveting and bolting.

Forge welding has been around almost since people began to work with metals. Then, in the late 19th century, Sir Humphrey Davy discovered the electric arc, and modern welding was born. The materials that welders use have changed over the years and today include not just metals but also polymers, ceramics, and composite and engineered materials. Lasers, electron beams, and plasma arcs supplement traditional electric and torch welding methods. Yet for all this history, basic knowledge about the welding process is surprisingly sparse. Conventional inspection techniques are not adequate to indicate how a weld evolves in time. Welding may be old, but the science of welding is in its infancy.

Livermore has a vital interest in knowing all it can about welding. Dependable welds are important for maintaining the performance and safety of nuclear weapons. Welds will also play a key role in the success of the Department of Energy's planned repository for long-term storage of nuclear wastes, which will potentially be located at Yucca Mountain in the Nevada desert. Waste canisters will have three layers of containment: a convenience can inside an inner can inside an outer can. The lids of the inner and outer cans will be welded shut. The canistered waste must remain impervious to attack by air, moisture, and the surrounding environment for thousands of years. All told, more than 100 miles of welds will be required at the repository.

Metallurgist John Elmer, Livermore's expert on welding, has been researching details of the welding process since the early 1990s with physical chemist Joe Wong, whose specialty is synchrotron x-radiation experiments. They are currently working with another metallurgist, Todd Palmer. The three are also collaborating with colleagues at Pennsylvania State University and Oak Ridge National Laboratory.

Over the last several years, the team has succeeded in producing maps of the microstructural changes that occur in and around the weld area as a metal melts and resolidifies. More recently, their experiments have revealed second-by-second changes in a metal's microstructure during welding. In contrast, conventional diagnostic techniques can examine the material only before and after welding or can derive information about changes only indirectly and after the fact. "These experiments at Livermore have given us the first real-time look at the welding process," says Lou Terminello, division leader in the Chemistry and Materials Science Directorate.

## Welds Take the Heat

When two pieces of material are being welded together, high heat rapidly melts the solid material, which quickly cools and solidifies again as the heat source moves away. Adjacent to the immediate weld area, or fusion zone, is the heat-affected zone (HAZ). As the name HAZ implies, the material there is affected by the high heat of the welding process but does not melt.

Heat causes changes in the material. The three well-known basic phases of a material are gas, liquid, and solid. But for many materials, multiple solid phases exist at various temperatures or at various combinations of temperature and pressure. At sea level—1 atmosphere—plain old $H_2O$ may form several kinds of ice, each of which is a different solid phase. Iron undergoes three solid-state phase transformations as its temperature increases from room temperature to 1,535°C, where it melts. Carbon also has several solid phases, including graphite and diamond. No one would confuse graphite and diamond. Each one is still carbon, but their crystal structures are very different.

When a material is welded, its crystalline structure changes. It is these microstructural changes that interest

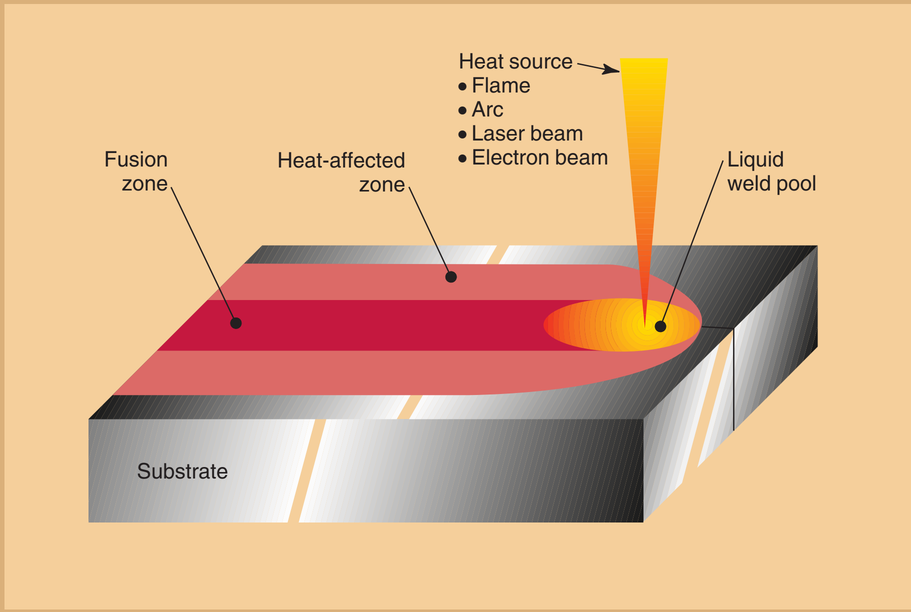



Illustration of a fusion weld. A liquid weld pool is created through the interaction of an intense heat source and the substrates being joined. Melting on the front side of the weld pool eliminates the interface between the materials, while solidification on the back side of the weld pool fuses the substrates together to create a solid joined part. Surrounding the fusion zone is a heat-affected zone, where the substrate is heated to temperatures up to the melting point of the metal being joined. Solidification in the fusion zone and solid-state phase transformations in the heat-affected zone are responsible for dramatic changes in the microstructure and properties of the welded joint.

Elmer. They can affect the strength of the material as well as its corrosion resistance, ductility, and mechanical properties. Any or all of the changes could either enhance the quality of the weld or reduce the weld's integrity. "We want to be able to understand the welding process by modeling it and then predict the changes that will occur," says Elmer. "But first, we need to gather real experimental data during welding to understand the fundamental properties of the process."

## Synchrotron Is Key

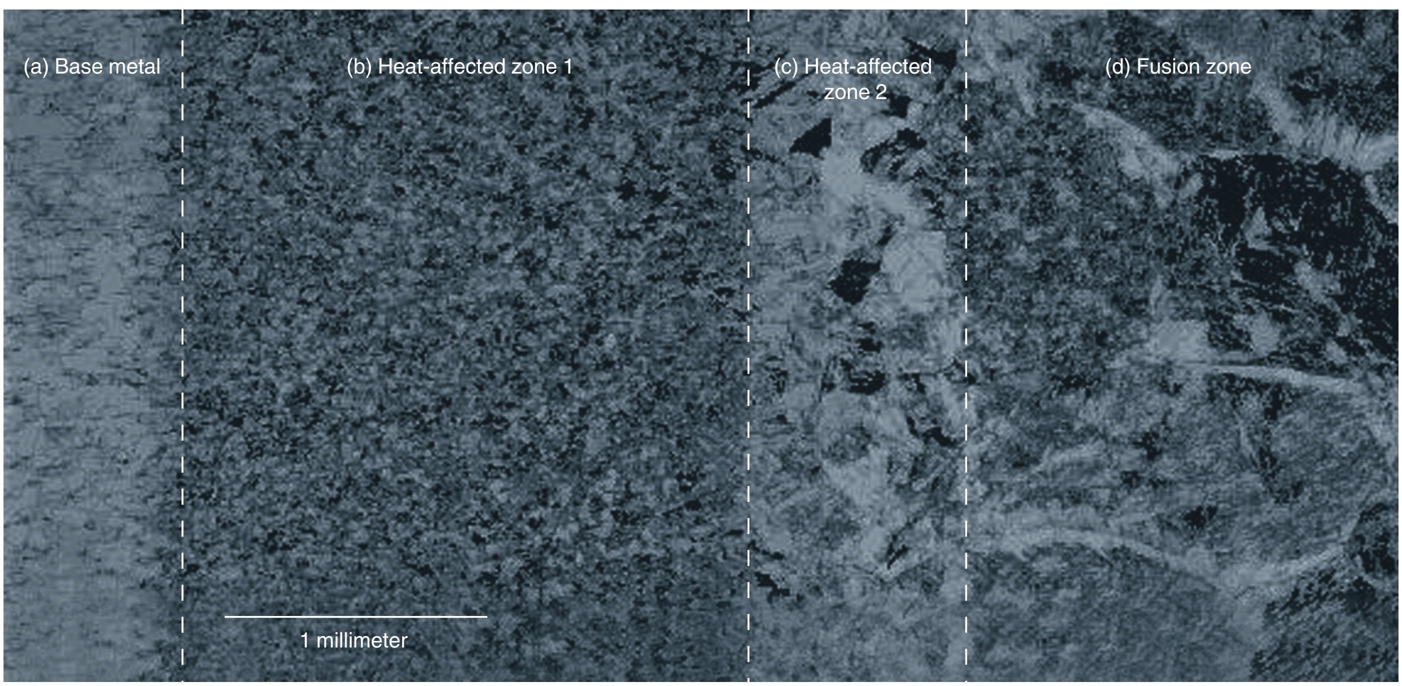
Joe Wong has been performing experiments with synchrotron radiation to examine materials for the past two decades. He and others helped to develop the experimental facility at the Stanford Synchrotron Radiation Laboratory back in 1977.

Synchrotron radiation is a particularly intense form of electromagnetic radiation. Highly energetic charged particles traveling at almost the speed of light and deflected in a magnetic field emit synchrotron radiation. This intense, highly collimated radiation—millions of times more powerful than that from a conventional x-ray tube—can probe the atomic structure and electronic states of matter. Experiments that would have taken hours with an x-ray tube source take milliseconds instead.

Synchrotron radiation spans the electromagnetic spectrum from infrared to hard x rays. X rays are ideal for probing matter because the wavelength of x-radiation is about the same size as an atom. Thus, with synchrotron x rays, the team can make direct observations of phase transformations in welds, watching microstructural changes as they evolve.

Synchrotron radiation sources at Stanford and elsewhere around the world are used by scientists working in many fields—by materials scientists like Elmer and Wong to study the dynamic properties of solid and amorphous materials, by biomedical researchers to study proteins and other large biomolecules, by medical workers for coronary angiography and other forms of imaging, and by geologists for structure characterizations and trace-element analyses of minerals.

The Livermore team is using x rays from the 31-pole x-ray "wiggler" at Stanford Synchrotron Radiation Laboratory for their experiments. In this device, an x-ray beam wiggles between an array of 31 magnetic poles, gathering intensity along the way. By carefully




Room-temperature top view of the microstructure of titanium from the fusion zone, through the heat-affected zone, and into the base metal (30 times magnification): (a) the base metal, (b) the small-grained portion of the heat-affected zone where the gamma phase has partially transformed to the beta phase, (c) the large-grained portion of the heat-affected zone where gamma-phase titanium has fully transformed into the beta phase, and (d) the fusion zone. Note the dramatic changes in grain structure.

directing this small, intense synchrotron beam at a given location in a weld, they can obtain an x-ray diffraction pattern to identify the phases present in the material at that location during the welding process. The x-ray diffraction pattern depends on the atomic structure of the material. “The diffraction pattern is the fingerprint of a material’s crystal structure,” says Wong. “Liquid is chaotic with no long-range order,” he continues, “so there is no diffraction.”

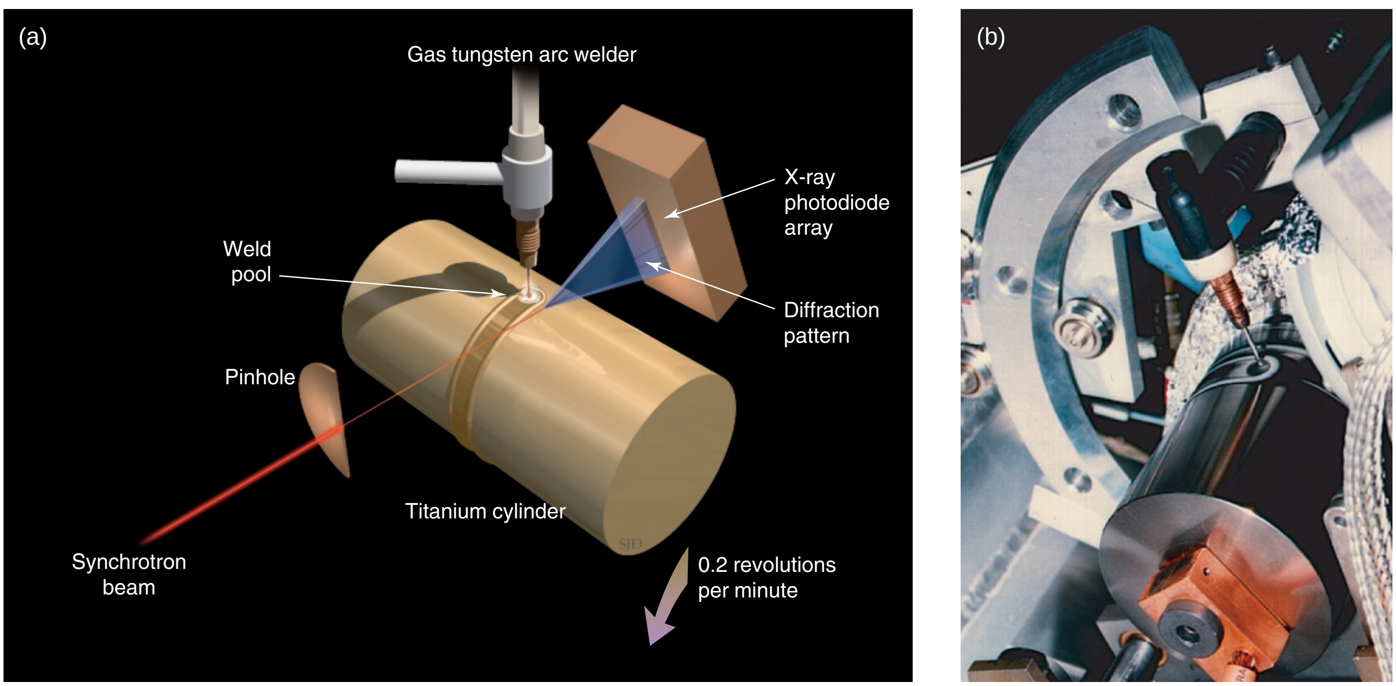
### From Simple to Complex

The team’s first experiments examined titanium welds. Titanium is popular in manufacturing because of its corrosion resistance and light weight. Also, titanium has two well-characterized solid-phase transitions at ambient air pressure before it melts. In pure titanium, the alpha phase exists from room temperature to 882°C. At these temperatures, titanium has a hexagonal-close-packed crystalline structure. At 882°C, pure titanium’s crystalline structure changes to the beta (body-centered-cubic) phase, which it maintains until it reaches the liquid phase at 1,670°C. As the liquid titanium cools, the phase transformations are reversed. Because these phase transformations occur over such a wide temperature range, titanium is a relatively easy material to study.

Using the experimental setup shown in the figure below, a metal bar rotates under a gas tungsten arc, taking 6 minutes for a full revolution. An intense x-ray beam from the synchrotron source passes through a pinhole to allow researchers to resolve features as small as 180 micrometers. During welding, the x-ray beam is aimed at specific points around the heat source. A silicon photodiode linear array detector records the diffraction patterns during the experiment.

The team maps phase transformations by performing a series of sequential linear scans from the centerline of the weld and out into the HAZ. In every row, 30 to 40 x-ray diffraction patterns are collected, spaced 0.25 millimeters apart. Each row requires one revolution of the cylinder. After completion of the first row, the welding heat source is moved 1 millimeter from its previous position to collect data in the next row, and so on.

This spatially resolved x-ray diffraction (SRXRD) technique is unique to Livermore for the study of welding. “Spatial resolution is the key to collecting useful in situ phase transformation data during welding,” says Elmer.




(a) A rendering of (b) the experimental setup for real-time investigations of welds using synchrotron radiation. The x-ray beam enters from the lower left through a pinhole to provide spatial resolution of 180 micrometers. During welding, this spatially resolved beam is aimed at a specific location of the weld where diffraction takes place. The diffracted beams are captured in real time using a silicon photodiode linear array detector. The weld is produced by a gas tungsten arc on a revolving solid bar of the material being studied.

The grain structure of commercially pure titanium—or any solid material for that matter—changes during welding. It is subjected to peak temperatures hundreds of degrees higher than the melting point, followed by rapid cooling. These temperature fluctuations alter the microstructure of the material nonuniformly to create the HAZ adjacent to the weld fusion zone. Solid-state phase transformations that occur in the HAZ create gradients of both microstructure and properties between the liquid metal in the fusion zone and the unaffected base metal farthest from the weld. Within the HAZ, the most severe microstructural changes occur close to the fusion zone, where the peak temperatures are the highest.

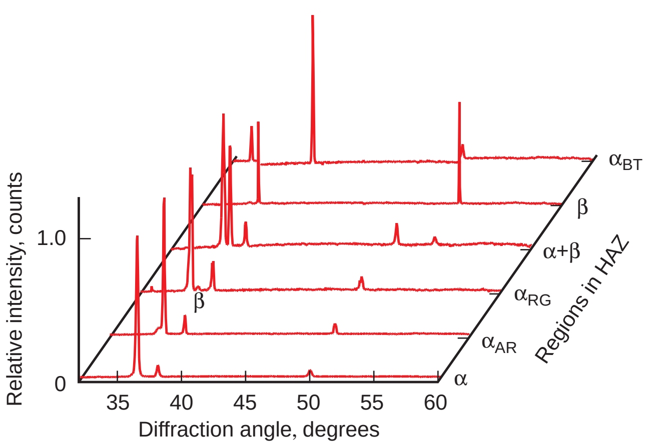
Researchers had suspected for some time that annealing and recrystallization occur in the colder portions of the HAZ in titanium. They also knew that both partial and complete alpha-to-beta transformations take place in the hotter portions of the HAZ. But what they had not been able to determine was the exact size and location of these regions.

Using SRXRD, the Livermore team found six regions in the HAZ around the liquid titanium weld pool, each with an identifiable diffraction pattern. From their diffraction data, they could follow the evolution of the phase transformations, at various locations and at various temperatures. This research resulted in a diffraction map of the HAZ [part (c) of the figure below] that shows the location of all the phases with respect to the transition temperatures.

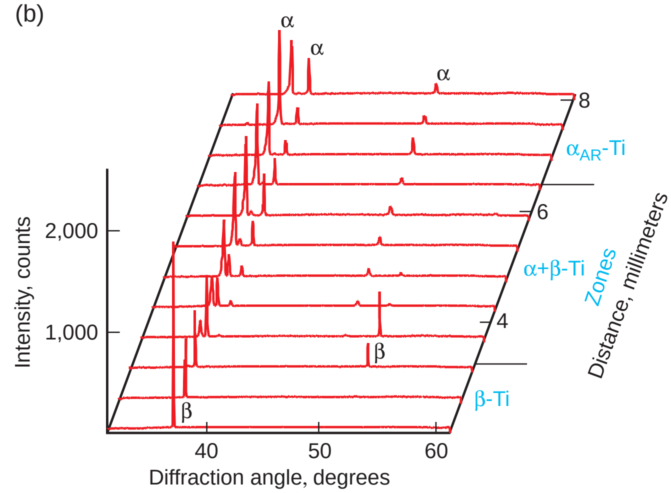
"Titanium was a good place to start with our experiments," says Elmer. "But steels are welded much more frequently." So their next sets of experiments dealt with carbon–manganese steel and stainless steels. While these alloys have more complex phase changes than pure metals, their phase transformations can be studied with the SRXRD technique.

Duplex stainless-steel alloys consist of austenite and ferrite solid phases, each of which has different crystal structures and magnetic properties. Here, they found five principal phase regions between the

(a)

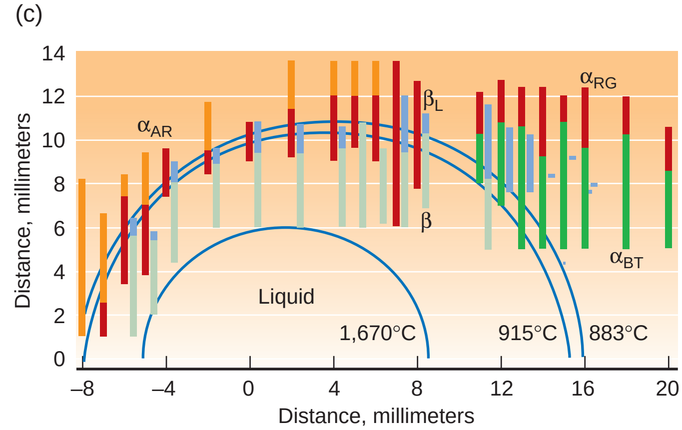



(b)




(a) These typical diffraction patterns from titanium welds represent the six different regions (on the right axis) that exist in the heat-affected zone (HAZ) during welding. (b) Evolution of spatially resolved x-ray diffraction patterns measured across the alpha-to-beta (α to β) phase transformation isotherm (temperature = 915°C) in titanium (Ti). Three zones are shown on the right axis: alpha-phase titanium ($\alpha_{AR}$-TI), alpha–beta (α+β-Ti) coexistence zone, and beta-phase titanium (β-Ti). (c) A spatially resolved x-ray diffraction phase map showing the locations of all the titanium diffraction patterns with respect to the transition temperatures for a titanium weld. The welding heat source is located at 0 on the horizontal axis.

(c)



liquid weld pool and the unaffected base metal that contribute to the final microstructure observed in the HAZ.

## Changes over Time

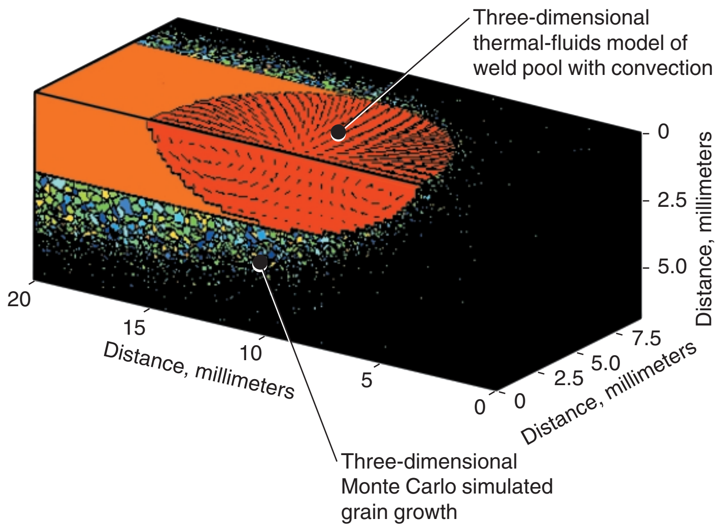
Phase mapping experiments performed using the SRXRD method are useful for observing phase changes under quasi-steady-state heating and cooling conditions. The next step was to examine the changes that occur at a single spot as a function of time. Wong developed a time-resolved x-ray diffraction (TRXRD) technique that takes a set of x-ray diffraction patterns at a single location adjacent to or within a stationary spot weld. When the detector is clocked for durations of tens to hundreds of milliseconds, phase transformation may be observed on a much shorter time scale than is possible with moving welds. Changes in the diffraction pattern show directly how phase changes are taking place as a function of time and temperature. As the temperature goes up and then down, the metal at the weld becomes liquid and then solidifies. With TRXRD, the Livermore team has been able to examine the solidification and subsequent solid-state phase transformations in a number of different materials for the first time.

For example, TRXRD has proved useful for examining the solidification behavior of austenitic stainless steels. In these stainless steels, the presence of residual ferrite in the austenitic microstructure affects the integrity of welds. Researchers have long been interested in understanding how residual ferrite in the microstructure evolves. For more than 50 years, those who work with welds have known that the composition of the weld is important and have developed methods for assuring that the austenite–ferrite ratio was appropriate for each specific need. Numerous studies have examined the rate of solidification, which affects the microstructure and relative percentage of austenite and ferrite in the final weld.

But Livermore was the first to make direct observations of the ferrite and austenite phases and the dynamics of this transformation. The Livermore team found directly, for the first time, that ferrite is the first phase to solidify from the liquid weld pool in a 304 stainless-steel alloy. The ferrite phase existed as the only solid phase for 500 milliseconds before beginning to transform into the austenite phase. The ferrite-to-austenite transformation took an additional 200 milliseconds of cooling, during which both phases coexist. The combined results showed that the majority of the ferrite phase transformed to the austenite phase by the time the weld had cooled to a temperature of 1,100°C.

## Beginning to Predict

Elmer and Palmer have also worked with modeling experts at Pennsylvania State University, where a research group has spent many years developing models to predict the temperatures present throughout a weld. By combining the results of the SRXRD experiments with the modeling results, the evolution of observed phase transformations can be more fully understood. As part of their collaboration, they performed three-dimensional Monte Carlo simulations




Three-dimensional Monte Carlo simulation of grain-size evolution in welds.

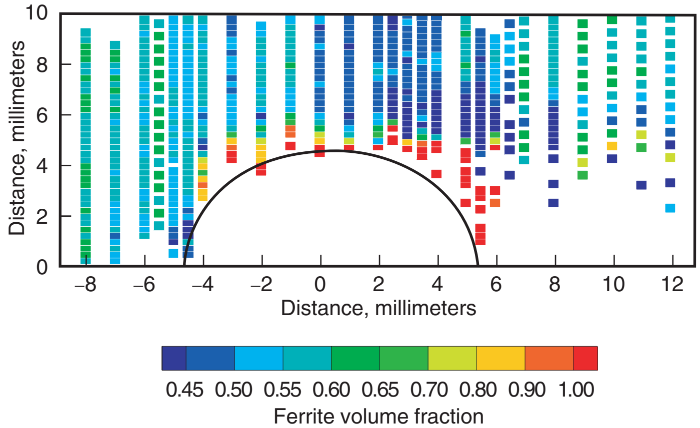

Infrared image of a duplex stainless-steel weld obtained in real time during a synchrotron experiment.

of the growth of grains during gas tungsten arc welding of titanium, shown in the figure on the left on p. 9.

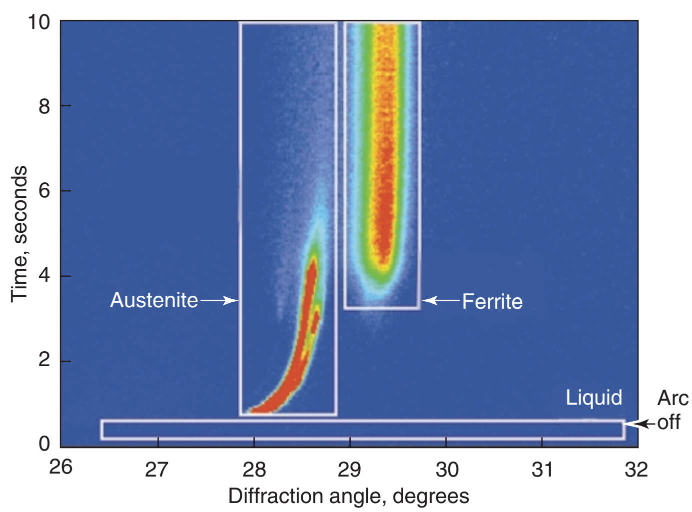
The Livermore–Penn State collaboration has continued to study phase transformations in duplex stainless steels. SRXRD observations of the phases present around the weld pool of an arc-welded 2205 duplex stainless steel have been combined with the results of a Penn State heat-transfer model to produce a thorough map of the phase transformations occurring in the heat-affected zone. An infrared image of a duplex stainless-steel weld, taken during the synchrotron experiments, is shown in the figure on the right on p. 9.

Further analysis of the data available in the diffraction patterns allowed the team to determine the amount of ferrite and austenite present at each location. The top figure below shows the variation in the ferrite volume fraction as a function of location around the weld pool. This is the first time the phenomenon was observed and quantified.

Once again demonstrating its unique capabilities, the SRXRD technique allowed the team to observe a decrease in the ferrite volume fraction at rather large distances from the weld pool (on the order of 9 millimeters). This change in the ferrite volume fraction was unexpected and had not been previously observed. Because evidence for this reaction disappears as the welding process continues, SRXRD provides the sole means available for monitoring these phase transformations.




Results of a spatially resolved x-ray diffraction experiment portray the dominant phase transformations and the regions over which they occur in the heat-affected zone during welding of duplex stainless steel.




Time-resolved x-ray diffraction results show phase transformations during weld solidification and cooling of a flux-cored arc-welding electrode.

## Research Leads to Smarter Welds

This pioneering work is not going unnoticed by the welding research community. Elmer was named a Fellow of the American Welding Society in 2000. And in May 2001, the society honored a paper by Elmer, Wong, and colleagues at Penn State with the prestigious William Spraragen Memorial Award. Their article on modeling of titanium welding was selected the best paper of 2000 in the *Welding Journal Research Supplement*.

The ultimate purpose of all research on welding is to move useful information out to the welders of the world, to help them make better welds. In fact, Livermore synchrotron investigations of welds, combined with computer modeling and postweld characterization of microstructure, are beginning to do just that.

Powdered filler metal additions, which include aluminum, in flux-cored arc-welding electrodes alter the microstructure and properties of the resulting welds in unpredictable and undesirable ways. In the bottom figure at the left, TRXRD results show phase transformations during the solidification and cooling of a weld in a mild steel consumable welding electrode. This figure comprises over 500 diffraction patterns, taken at the rate of 20 patterns per second, and indicates an unexpected nonequilibrium solidification of the weld.

Nonequilibrium solidification translates into a possible safety hazard for welded structures. To mitigate the hazard, this research, which is being done in collaboration with Oak Ridge National Laboratory, is now being used to help design new self-shielded welding electrodes with improved weld properties for safer building and bridge construction. You can't get much more useful than that.

—*Katie Walter*

**Key Words:** fusion welding, phase transformation, solidification kinetics, spatially resolved x-ray diffraction (SRXRD), stainless steel, synchrotron radiation, time-resolved x-ray diffraction (TRXRD), titanium, x-ray diffraction.

***For further information contact John Elmer (925) 422-6543 (elmer1@llnl.gov) or Joe Wong (925) 423-6385 (wong10@llnl.gov).***

## About the Scientists

JOHN ELMER received his B.S. and M.S. in metallurgical engineering from the Colorado School of Mines in 1979 and 1981, respectively, and his Sc.D. in metallurgy from the Massachusetts Institute of Technology in 1988. After working briefly at Lawrence Livermore in the early 1980s, he rejoined the Laboratory as a postdoctoral scientist in 1988 and was named group leader for Materials Joining in 1989, a position he continues to hold. The group is responsible for electron- and laser-beam welding, vacuum brazing, and diffusion bonding.

Elmer has written or cowritten over 60 technical papers on materials joining, metallurgy, rapid solidification, the interactions of high-energy-density beams and materials, and the kinetics of phase transformations under nonisothermal conditions. He is a member of the American Welding Society (AWS) and the American Society of Metals International. In 2000, he was made a fellow of AWS; in 1991 and 2000, he received the William Spraragen Award from AWS; and in 1995, he received the Professor Masubuchi-Shinsho Corporation Award from AWS.

JOE WONG received a B.Sc. in pure and applied chemistry in 1965 and a B.Sc. in physical chemistry in 1966 from the University of Tasmania, Australia. In 1970, he received his Ph.D. in physical chemistry from Purdue University, and in 1986, he received a D.Sc. from the University of Tasmania. In 1986, he joined Lawrence Livermore as a senior chemist.

Wong's primary research interests include glass science and materials science. He has also examined the chemical dynamics and phase transformation of various materials and processes using high-resolution electron microscopy, various kinds of spectroscopy, and novel synchrotron instrumentation. He has written or cowritten over 175 journal articles, holds 7 U.S. patents, and has received numerous prizes and awards, most recently (with John Elmer) the William Spraragen Memorial Award from the American Welding Society for the best paper published in *Welding Journal Research Supplement* in 2000.